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Fate of Quantum Anomalies for 1d lattice chiral fermion with a simple non-Hermitian Hamiltonian

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Abstract: It is generally believed that the 1+1D model for a single chiral fermion does not exist by itself alone on lattice. The obstruction to such a lattice realization is the failure to reproduce the quantum anomalies of a chiral fermion in continuum. The conventional way to escape is to associate the anomalous 1d system with a 2d bulk, which is in a topologically non-trivial state, as the boundary of the latter. In this paper, we propose a 1+1D chiral fermion model on 1d spatial lattice, *standing alone* — without being associated with a 2d bulk — with a simple *non-Hermitian* hopping Hamiltonian. We demonstrate, using various methods, that the model possesses the same chiral anomaly and gravitational anomaly as in continuum theory. Furthermore, with appropriate parameters, the low energy effective theory of the model remains a field theory for unitary chiral fermions. The essential reason for the success is that the usual "doubled" fermion mode with opposite chirality is rapidly damped out because of non-Hermicity of the Hamiltonian.

Keywords: Anomalies in Field and String Theories, Lattice Quantum Field Theory

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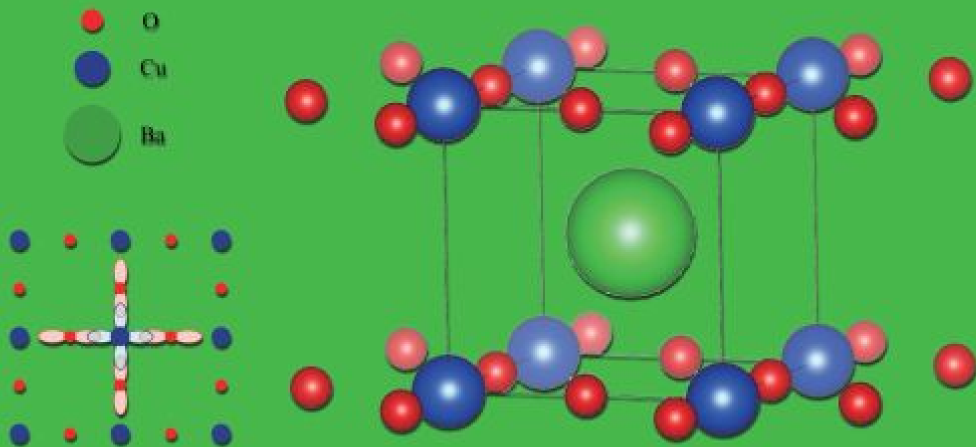

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特邀综述

重整化平均场理论及其在铜氧化物高温超导材料中的应用

易伟柱,奚文杰,陈伟强

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【摘要】 对铜氧化物高温超导体的研究是凝聚态物理中最重要的问题之一.理论研究上的困难在于铜氧化物高温超导材料中单占据条件所导致的强关联效应.铜氧化物高温超导材料可以用 t-J 模型进行描述,而上述的单占据条件则体现于 t-J 模型中的 Gutzwiller 投影算符.重整化平均场理论(RMFT)是一种处理这类由 Gutzwiller 投影算符所导致的强关联效应比较有效的方法.本文首先对铜氧化物高温超导材料进行简单的介绍.然后我们将重点介绍 Gutzwiller 近似.最后我们会介绍重整化平均场理论,以及其在铜氧化物高温超导材料和其他一些强关联材料中的应用.

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Renormalized Meanfield Theory and its Application in High Temperature Cuprate Superconductors

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【Abstract】 The high temperature cuprate superconductors are one of the most important field in condensed matter physics. The main theoretical difficulty in the study is the strongly correlation effect originated from the single occupation condition, which is tracked by the Gutzwiller projection in the t-J model. The renormalized mean field theory can be used to deal with the Gutzwiller projection in such kinds of situations. In this paper, we will briefly introduce the cuprate superconductor first. Then, we will focus on the Gutzwiller approximation, which is crucial for the subsequent renormalized mean-field processing. Finally, we will introduce the RMFT theory, and its application in cuprate superconductors and other strongly correlated systems.

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Temporal evolution of one-dimensional fermion liquid with particle loss

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Intriguing phenomenon emerge with the sacrifice of Hermicity in quantum systems, which can be complemented in open system. Open quantum systems behave non-trivially from closed systems especially in temporal evolution. In this work, we study the dynamical properties of a generic one-dimensional fermionic system with particle loss. The short-time behavior of the system is described by a non-Hermitian effective Hamiltonian, while the long-time dynamics is governed by Lindblad master equation. We show that the time-dependent von Neumann entropy with spatial bipartition of the system has universal behaviors hinging on the Liouvillian spectra. On account of thermalization, the entropy increases rapidly in short time when turning on the quantum jumps. Whether the Liouvillian gap closes or not affects the long-time decaying. The left-right asymmetry of quasiparticles in momentum space is observed as a result of non-reciprocal hopping in the effective Hamiltonian induced by correlated quantum-jump operators. This will also induce an interaction-strength-independent momentum-space entanglement in early time. The phenomenon in momentum-space share the same origin with the renowned non-Hermitian skin effect.

Introduction.– Open quantum system and non-Hermitian physics have become an increasingly attractive topic for research . In recent years, there are lots of important findings in this area, both theoretically[1–11] and experimentally[12–21]. Especially, in condensed matter physics, there have been lots of studies focusing on non-Hermitian skin effect[22–30], symmetry and topology of non-Hermitian quantum phases[22, 24, 27, 31–45], the quantum phase transition and quantum criticality of non-Hermitian systems[46–52], and the exceptional points in non-Hermitian system [28, 33, 34, 53–55]. However, most of them are based on the non-Hermitian band theory and short-time dynamics [6, 15, 56–60], which derives from a single-particle non-Hermitian Hamiltonian. Though the effective non-Hermitian Hamiltonian can describe certain effects in many cases, it fails to capture the long-time features of the open system due to its limitations. Therefore, a study of many-body non-Hermitian problem with the long-time dynamics taken into account is in demand. Generally speaking, the non-hermiticity of the effective Hamiltonian of an open system mainly comes from the coupling between the system and its environment. It can be contained in the self-energy of single-particle Green's function resulting from the interactions, or equivalently it can be induced by coupling to a Markovian environment while neglecting quantum jumps or by postselection[61, 62]. Complementing this short-time effective description, the full dynamics is governed by the so-called Lindblad master equation[63, 64],

$$\dot{\rho} = \mathcal{L}[\rho] := -\mathrm{i}[H_0, \rho] + \sum_i \left(L_i \rho L_i^\dagger - \frac{1}{2}\left\{ L_i^\dagger L_i, \rho \right\} \right) \tag{1}$$

where ρ is the density matrix of the system, L_is are jump operators originating from the coupling between the system and the environment. The effective non-Hermitian Hamiltonian expresses as $H_{\text{eff}} = H_0 - \frac{i}{2}\sum_i L_i^\dagger L_i$ by ignoring $L_i \rho L_i^\dagger$ terms.

Recent progress in quantum information provides some novel tools to study quantum many-body systems, among that the von Neumann entropy (the entanglement entropy) is the most powerful in detecting system's universal properties, which is widely applied in multifarious fields[65–67]. In the case of zero-temperature gapped quantum system, the entanglement entropy follows the area law[66, 68, 69]. For critical systems, entanglement entropy has logarithmic scaling behavior[66, 70, 71]. Under temporal evolution, Von Neumann entropy also tracks the universal dynamical properties of correlations in various systems, including unitary[72–77] or non-unitary quantum quench[78, 79], and generic dissipative system[80–83] and generic stochastic [84–92] dynamics in isolated, time-periodic driven system[93–96], or non-equilibrium systems[90, 97–99].

In this letter, we study a generalized dimerized model whose coupling to the environment is described by dissipative quantum-jump terms. It is observed that the effective Hamiltonian shares particular information with the Liouvillian in terms of eigenspectrum. Via the solving of time-dependent correlation function, we show that long-time behavior is also highly related to the effective non-Hermitian Hamiltonian albeit not governed by it. Through time-dependent correlation matrix method we see the univeral features can be reflected by system's time-dependent entropy. We show that when the quantum jumps are turned on, the system's entropy surges in a short time signaling it quickly thermalized. The entropy then decreases, which manifests the quantum dissipative effect. The decaying behavior depends not on whether

Exceptional entanglement in non-Hermitian fermionic models

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Exotic singular objects, known as exceptional points, are ubiquitous in non-Hermitian physics. They might be spectral singularities in energy bands that produce anomalous effects and defectiveness. The quantum entanglement of a generic non-Hermitian model with two different types of spectral exceptional points (SEPs) is systematically investigated in this paper. We discovered a relationship between non-unitary conformal field theories and the k-linear-type SEPs, which is typically associated with $\mathcal{PT}$-symmetry or pesdo-Hermicity spontaneous breaking. The underlying association between k-square-root-type SEPs, which arise concurrently with real (imaginary) gap closing in the complex spectrum, mimicking first-order-phase-transition criticalities, and complex conformal field theories (cCFTs) is addressed through the calculation of complex central charges. From the entanglement spectrum, zero-energy exceptional modes are found to be distinct from normal zero modes or topological boundary modes. Finally, we include a brief discussion of analogous non-Hermitian quantum spin models and endeavor to establish an intuitive understanding of exceptional points through the spin picture in various scenarios.

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I. INTRODUCTION

Exceptional points (EPs) [1] are spectral singularities in the parameter space of non-Hermitian quantum systems. At EPs, certain of the eigenvectors and their corresponding eigenvalues coalesce, leading to anomalous degeneracies [2, 3]. Due to their rich physics and potential for novel applications, exceptional points and phenomena associated with them have become central subjects of study in non-Hermitian quantum physics [4–21]. In particular, the topological structures of EPs in dynamically encircling them have been discussed widely [9, 22–31] and demonstrated in various systems including optical photonics [32–37] and spin, ion, superconducting quantum simulators [38–40]. Other intriguing properties ranging from intrinsic chirality [41, 42] to unidirectionality [43–45], as well as enhanced sensitivity at exceptional points [46–48] also attract a lot of attention.

EPs are typically studied in $\mathcal{PT}$-symmetric systems as the gap closing points or the imaginary spectra emerging points due to the spontaneous $\mathcal{PT}$-symmetry breaking. Generic EPs, however, will have completely different stories. While engineering and detecting of exceptional points or their higher-dimensional extensions [33, 49, 50] have been accomplished in a variety of few-body systems [32, 34, 35, 48, 51, 52], the features of true many-body systems with EPs, such as their spectral and eigenstate properties, as well as singular behaviors of relevant observables and entanglement properties in the vicinity of EPs, remain largely unexplored.

Gapless spectra emerge along with EPs in the momentum spaces, referred to as spectral exceptional points (SEPs) in bands. In contrast to Hermitian gapless systems, generic non-Hermitian Hamiltonians have complex energy spectrums and the EPs are branch points on the complex energy Riemann surface.

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For Hermitian systems, it is well established that the entanglement entropy scales universally as $S \sim (c/3)\log l$ in the $1+1$ dimensional critical system, where l denotes the size of the subsystem and c denotes the central charge of the related conformal field theory [53–55].In fermionic systems, c is closely related to the nodal points on the Fermi surface, which cause discontinuities in state occupation [56]. In some gapless non-Hermitian systems without EPs, as in Hermitian systems, the positive central charge is related to the real spectral Fermi points [57, 58].

However, when non-Hermitian gapless systems incorporate SEPs, the preceding statement becomes invalid. The central charge has ceased to be positive and no longer displays a naive connection with the Fermi points. Several well-known examples include the 1+1 d Yang-Lee edge singularity [59, 60]. They retain conformal symmetry despite their non-unitary nature and exhibit universal logarithmic scaling of entanglement entropy [61, 62]. The low-energy theory for such a critical non-Hermitian model is believed to be a non-unitary conformal field theory.

Recently, non-unitary conformal field theories (nUCFTs) have attracted particular interest. It is demonstrated that nUCFTs not only emerge from the phase transition of classical statistical models or the $\mathcal{PT}$-phase transition of non-Hermitian quantum models, but also are connected to non-unitary topological orders [63–68]. A major difference between non-unitary and unitary CFTs is that the central charge and conformal weights of some primary fields are negative in non-unitary CFTs. In contrast, they are all positive in unitary CFTs. The physical ground state no longer coincides with the conformal vacuum due to negative conformal weight. Additionally, there is a specialized version of non-unitary conformal field theories with complex central charges known as complex conformal field theories (cCFTs) [69–72].

They might occur in some weakly first-order phase transitions, such as those found in the $Q > 4$ Potts